Modeling and Stability Analysis of Nonlinear Networked Control Systems Based on Quasi T-S Fuzzy Model

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Abstract

This study presents a two-level Quasi T-S fuzzy (QTS) model to represent nonlinear networked control systems (NCS), which takes the performance of network with time-delay and data packet dropouts into the investigations. At the working points of nonlinear NCS, regard the subsystem as linear system modelling by QTS, then the global model of nonlinear is fuzzy fused by linear subsystem. This study constructs the corresponding system model, in which the system's stability is proved with linear matrix inequality (LMI). As a bench test a nonlinear system is selected to demonstrate the feasibility and efficiency though numerical analysis. This study provides a new method of fault diagnosis and tolerance control of nonlinear NCS.

Keywords

Nonlinear Networked Control System; Quasi T-S fuzzy (QTS) model; Linear Matrix Inequality (LMI); Stability

Introduction

A nonlinear control system which node connected through a networked is called nonlinear networked control system, which features not only nonlinear, but also network-induced delay and data packet dropouts (Hong Zhang, Huajing Fang, Xianping Ren,Tonghui Qian,2012; Hong Zhang, Huajing Fang, Xianping Ren,2011; Huajing Fang, Hong Zhang, Yiwei Fang, and Fang Yang,2006; Huajing Fang, Fang Yang, Zheng Ying, and Hong Zhang,2006;).In our preliminary research, we have the thought of establishing quasi T-S fuzzy model targeted at linear networked control system, and we extend it into the nonlinear networked control system(. The basic design is as follows:

First of all, we assume that the nonlinear networked control system satisfies the following assumptions:

1)The nonlinear networked control system (NCS) has *m* working points, at each of which the system is deemed as subsystem with both long delay and data packet dropouts; the sampling period of the system is T_s , and delay is represented by τ , if $\tau \le nT_s$, it is deemed that no data are lost; if $\tau > nT_s$, it is deemed that information delivered is dropout (namely a data packet loss occurs).

2)meanwhile, each working point has

$$\mu = \{\mu_1, \mu_2, \cdots, \mu_n, \mu_{n+1}\},$$

Where

$$\mu_r = P((r-1)T_s < \tau \le rT_s) = P_r \quad r = 1,2,\cdots,n,$$

represents the probability of different delays;

$$\mu_{n+1} = P(\tau > nT_s) = P_{n+1} + P_{n+2} + \cdots$$

represents the sum of probabilities when the delay is larger than nT_s,and $\sum_{r=1}^{n+1}\mu_r = 1$

3)the maximum allowable comprehensive bound shall be defined according to the reference(Tanaka K, Wang H O,2001), which is the comprehensive upper bound of closed loop network delay, maximum continuous packet lost number, control system sampling period and other factors allowed by the NCS.

On this basis, we proposed analysis and design based on a two-level QTS fuzzy model of nonlinear NCS. The first level (outer layer): provided that the nonlinear NCS has *m* working points, we establish segmented linear subsystem model at the m working points based on the theory of T-S fuzzy model, and we may united *m* local models into a global model based on parallel compensated. The second level (inner layer): establish corresponding QTS model which considering time delay and data packet dropout in the

meantime.

System Model of Nonlinear NCS

Inner layer: Discussing the conditions of linear NCS system at working points，at the ith working point, the nonlinear system is deemed as a linear subsystem, and the corresponding QTS models are discussed under two kinds of conditions (refer to the stability analysis, robustness analysis, etc of networked control system based on quasi T-S model):

Model 1: The state information of the ith model transmitted by a sensor to the controller is lost, the previous state information is used as the current state information to construct controlled information, and the model of the linear subsystem based on fuzzy fusion as follow:

$$x(k+1)=\sum_{r=1}^{n}\mu_r[A_i x(k)+\sum_{j=1}^{n}\mu_j B_i F_{ij}x(k-r-j)+\mu_{n+1}B_i F_{i(n+1)}x(k-r-1)]+\mu_{n+1}A_i x(k)$$

$$=A_i x(k)+\sum_{r=1}^{n}\mu_r\sum_{j=1}^{n}\mu_j B_i F_{ij}x(k-r-j)+\sum_{r=1}^{n}\mu_r\mu_{n+1}B_i F_{i(n+1)}x(k-r-1) \quad (1)$$

$$y(k)=C_i x(k)$$

Model 2: When the state information transmitted by a sensor to the controller is lost, the first n state information are used in weighting method as the current state information to construct controlled information, and the model of the NCS system after fuzzy fusion is as follow:

$$x(k+1)=\sum_{r=1}^{n}\mu_r[A_i x(k)+\sum_{j=1}^{n}\mu_j B_i F_{ij}x(k-r-j)]+\mu_{n+1}B_i F_{i(n+1)}\sum_{j=1}^{n}\mu_j x(k-r-j)]+\mu_{n+1}A_i x(k)$$

$$=A_i x(k)+\sum_{r=1}^{n}\mu_r\sum_{j=1}^{n}\mu_j[B_i F_{ij}+\mu_{n+1}B_i F_{i(n+1)}]x(k-r-j) \quad (2)$$

$$y(k)=C_i x(k)$$

Provided the i th linear subsystem satisfies the fuzzy rule i $(i=1,2,...,m)$:

IF $z_1(k)$ is M_{i1}, $z_2(k)$ is M_{i2} ,…… $z_p(k)$ is M_{ip}

THEN the linear subsystem satisfies **Model 1** or **Model 2.**

Outer layer: Regard each working point as a fuzzy subsystem of nonlinear NCS, and each subsystem satisfies certain fuzzy rule i $(i=1,2,...,m)$：Provided the i th linear subsystem satisfies the fuzzy rule i $(i=1,2,...,m)$:

IF $z_1(k)$ is M_{i1}, $z_2(k)$ is M_{i2} ,…… $z_p(k)$ is M_{ip}

THEN the linear subsystem satisfies Model 1 or Model 2.

Thus the nonlinear NCS model can be obtained by using fuzzy fusion as follow: Model 3 or Model 4 .

Model 3：

$$x(k+1)=\sum_{i=1}^{m}\rho_i\{A_i x(k)+\sum_{r=1}^{n}\mu_r\sum_{j=1}^{n}\mu_j B_i F_{ij}x(k-r-j)+\sum_{r=1}^{n}\mu_r\mu_{n+1}B_i F_{i(n+1)}x(k-r-1)\} \quad (3)$$

$$y(k)=\sum_{i=1}^{m}\rho_i C_i x(k)$$

Model 4：

$$x(k+1)=\sum_{i=1}^{m}\rho_i\{A_i x(k)+\sum_{r=1}^{n}\mu_r\sum_{j=1}^{n}\mu_j[B_i F_{ij}+\mu_{n+1}B_i F_{i(n+1)}]x(k-r-j)\} \quad (4)$$

$$y(k)=\sum_{i=1}^{m}\rho_i C_i x(k)$$

where: $z_i(k), i=1,2,\cdots,p$,is the premise variables of the fuzzy rule of nonlinear system; M_{ig} , $i=1,2,\cdots,p$, $g=1,2,\cdots,p$ is corresponding subsystem; ω_i is the weight of membership of the i th subsystem, and now defined as:

$$\rho_i=\omega_i\Big/\sum_{i=1}^{m}\omega_i \;,\; \sum_{i=1}^{m}\rho_i=1$$

Stability Analysis of Nonlinear NCS

Theorem 1：As for nonlinear NCS (3), if there are positive definite matrix P and positive definite matrix Q, can be used

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & P \end{bmatrix}>0 \quad (5),$$

then the nonlinear system is asymptotic stability. Where the submatrix:

$$S_{11}=\begin{bmatrix} P-Q' & 0 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & \mu_1\mu_1 Q & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & 2\mu_1\mu_2 Q & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 2(\mu_1\mu_{n-1}+\mu_2\mu_{n-2}+\cdots+\mu_{\frac{n}{2}-1}\mu_{\frac{n}{2}+1})Q+\mu_{\frac{n}{2}}\mu_{\frac{n}{2}}Q & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 & \cdots & \mu_n\mu_n \end{bmatrix} \quad (6)$$

In the format $Q'=\sum_{r=1}^{n}\mu_r Q$, when n is odd number, the element of row n and line n in the matrix is: $2(\mu_1\mu_{n-1}+\mu_2\mu_{n-2}+\cdots+\mu_{\frac{n}{2}-1}\mu_{\frac{n}{2}+1})Q$, when n is even number, the element of row n and line n in the matrix is $2(\mu_1\mu_{n-1}+\mu_2\mu_{n-2}+\cdots+\mu_{\frac{n}{2}-1}\mu_{\frac{n}{2}+1})Q+\mu_{\frac{n}{2}}\mu_{\frac{n}{2}}Q$.

$$S_{21}=S_{12}^T= P\begin{bmatrix} A_i^T \\ (\mu_1\mu_1 B_\alpha F_{\alpha 1}+\mu_1\mu_{n+1}B_\alpha F_{\alpha(n+1)})^T \\ (\mu_1\mu_2 B_\alpha F_{\alpha 2}+\mu_2\mu_1 B_\alpha F_{\alpha 1}+\mu_2\mu_{n+1}B_\alpha F_{\alpha(n+1)})^T \\ \vdots \\ (\mu_1\mu_{n-1}B_\alpha F_{\alpha(n-1)}+\mu_2\mu_{n-2}B_\alpha F_{\alpha(n-2)}+\cdots\mu_{n-1}\mu_1 B_\alpha F_{\alpha 1}+\mu_{n-1}\mu_{n+1}B_\alpha F_{\alpha(n+1)})^T \\ \vdots \\ (\mu_n\mu_n B_\alpha F_{\alpha n})^T \end{bmatrix}^T \sum_{\alpha=1}^{m}\rho_\alpha \quad (7)$$

Proof: First construct the Lyapunov function:

$$v(k)=x^T(k)Px(k)+\sum_{r=1}^{n}\sum_{j=1}^{n}\sum_{s=k-r-j}^{k-1}\mu_r\mu_j x^T(s)Qx(s)>0$$

Then

$$v(k+1)=\{\sum_{i=1}^{m}\rho_i[A_i x(k)+\sum_{r=1}^{n}\sum_{j=1}^{n}\mu_r\mu_j B_i F_{ij} x(k-r-j)+\sum_{r=1}^{n}\mu_r\mu_{n+1}F_{i(n+1)}x(k-r-1)]\}^T P$$

$$\{\sum_{i=1}^{m}\rho_i[A_i x(k)+\sum_{r=1}^{n}\sum_{j=1}^{n}\mu_r\mu_j B_i F_{ij} x(k-r-j)+\sum_{r=1}^{n}\mu_r\mu_{n+1}F_{i(n+1)}x(k-r-1)]\}$$

$$+\sum_{r=1}^{n}\sum_{j=1}^{n}\sum_{s=k-r-j+1}^{k}\mu_r\mu_j x^T(s)Qx(s)$$

$$\Delta V(k)=V(k+1)-V(k)$$

$$=\begin{bmatrix} x(k)\\ x(k-2)\\ x(k-3)\\ \vdots\\ x(k-n)\\ \vdots\\ x(k-2n)\end{bmatrix}^T \sum_{i=1}^{m}\sum_{\alpha=1}^{m}\rho_i\rho_\alpha \begin{bmatrix} A_i^T \\ (\mu_1\mu_1 B_i F_{i1}+\mu_1\mu_{n+1}B_i F_{i(n+1)})^T \\ (\mu_1\mu_2 B_i F_{i2}+\mu_2\mu_1 B_i F_{i1}+\mu_2\mu_{n+1}B_i F_{i(n+1)})^T \\ \vdots \\ (\mu_1\mu_{n-1}B_i F_{i(n-1)}+\mu_2\mu_{n-2}B_i F_{i(n-2)}+\cdots\mu_{n-1}\mu_1 B_i F_{i1}+\mu_{n-1}\mu_{n+1}B_i F_{i(n+1)})^T \\ \vdots \\ (\mu_n\mu_n B_i F_{in})^T \end{bmatrix}$$

$$P\begin{bmatrix} A_i^T \\ (\mu_1\mu_1 B_\alpha F_{\alpha 1}+\mu_1\mu_{n+1}B_\alpha F_{\alpha(n+1)})^T \\ (\mu_1\mu_2 B_\alpha F_{\alpha 2}+\mu_2\mu_1 B_\alpha F_{\alpha 1}+\mu_2\mu_{n+1}B_\alpha F_{\alpha(n+1)})^T \\ \vdots \\ (\mu_1\mu_{n-1}B_\alpha F_{\alpha(n-1)}+\mu_2\mu_{n-2}B_\alpha F_{\alpha(n-2)}+\cdots\mu_{n-1}\mu_1 B_\alpha F_{\alpha 1}+\mu_{n-1}\mu_{n+1}B_\alpha F_{\alpha(n+1)})^T \\ \vdots \\ (\mu_n\mu_n B_\alpha F_{\alpha n})^T \end{bmatrix}^T \begin{bmatrix} x(k)\\ x(k-2)\\ x(k-3)\\ \vdots\\ x(k-n)\\ \vdots\\ x(k-2n)\end{bmatrix}$$

$$-x^T(k)Px(k)+\sum_{r=1}^{n}\sum_{j=1}^{n}\mu_r\mu_i[x^T(k)Qx(k)-x^T(k-r-j)Qx(k-r-j)]$$

thus from Formats (6) and (7) we can obtain:

$$\Delta V(k)=\begin{bmatrix} x(k)\\ x(k-2)\\ x(k-3)\\ \vdots\\ x(k-n)\\ \vdots\\ x(k-2n)\end{bmatrix}^T (S_{12}P^{-1}S_{12}^T)\begin{bmatrix} x(k)\\ x(k-2)\\ x(k-3)\\ \vdots\\ x(k-n)\\ \vdots\\ x(k-2n)\end{bmatrix}-\begin{bmatrix} x(k)\\ x(k-2)\\ x(k-3)\\ \vdots\\ x(k-n)\\ \vdots\\ x(k-2n)\end{bmatrix}^T$$

$$\begin{bmatrix} P-Q' & 0 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & \mu_1\mu_1 Q & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & 2\mu_1\mu_2 Q & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 2(\mu_1\mu_{n-1}+\mu_2\mu_{n-2}+\cdots+\mu_{\frac{n}{2}-1}\mu_{\frac{n}{2}+1})Q+\mu_{\frac{n}{2}}\mu_{\frac{n}{2}}Q & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 & \cdots & \mu_n\mu_n \end{bmatrix}\begin{bmatrix} x(k)\\ x(k-2)\\ x(k-3)\\ \vdots\\ x(k-n)\\ \vdots\\ x(k-2n)\end{bmatrix}$$

$$\Delta V(k)=-\begin{bmatrix} x(k)\\ x(k-2)\\ x(k-3)\\ \vdots\\ x(k-n)\\ \vdots\\ x(k-2n)\end{bmatrix}^T (S_{11}-S_{12}P^{-1}S_{12}^T)\begin{bmatrix} x(k)\\ x(k-2)\\ x(k-3)\\ \vdots\\ x(k-n)\\ \vdots\\ x(k-2n)\end{bmatrix}$$

Therefore, if $\Delta V(k)<0$, only if $(S_{11}-S_{12}P^{-1}S_{12}^T)>0$ based on the properties of Schur complement, namely

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & P \end{bmatrix}>0$$

Similarly, it also can be proved the stability of the nonlinear NCS system described by Model 4.

Simulation

For example of nonlinear system in reference (Yue D, Han Q L,2006). Using two-level Quasi T-S fuzzy model to describe the system as follow:

$$x_1(k+1)=x_2(k)+\sin x_3(k)+x_1^2(k)u(k)$$
$$x_2(k+1)=x_1(k)+2x_2(k)$$
$$x_3(k+1)=x_1^2(k)x_2(k)+x_1(k)$$
$$x_4(k+1)=\sin x_3(k)$$

$$y_1(k)=(1+x_1^2(k))x_4(k)+x_2(k)$$
$$y_2(k)=x_2(k)+x_3(k)$$

Suppose the sample period of NCS is $T=0.05s$,and the probability distribution of every subsystem with time-delay or data packet dropout is similar as follow: $\mu=\{0.3,0.5,0.1,0.1\}$,where μ_1,μ_2 and μ_3 is the probability of time-delay, μ_4 is the probability of time-delay above three times of sample time, therefore the nonlinear system can be fused by four sub-linear systems; each subsystem composed of four systems; using $x_1(k)$ and $x_3(k)$ as premise variable of out layer system, where $x_1(k)\in[-a,a]$, $x_3(k)\in[-b,b]$,then the membership function of system is:

$$M_{11}(x_1(k))=\frac{x_1^2(k)}{a^2},M_{21}(x_1(k))=1-\frac{x_1^2(k)}{a^2}$$

$$M_{12}(x_3(k))=\begin{cases}\dfrac{b\cdot\sin x_3(k)-\sin b\cdot x_3(k)}{x_3(k)\cdot(b-\sin b)}, & x_3(k)\neq 0\\ 1 & ,x_3(k)=0\end{cases}$$

$$M_{22}(x_3(k))=\begin{cases}\dfrac{b\cdot(x_3(k)-\sin x_3(k))}{x_3(k)\cdot(b-\sin b)}, & x_3(k)\neq 0\\ 0 & ,x_3(k)=0\end{cases}$$

The system matrix、input matrix and output matrix of four subsystem of inner layer is:

$$A_1=\begin{bmatrix}0&1&1&0\\1&2&0&0\\1&a^2&0&0\\0&0&1&0\end{bmatrix},\quad A_2=\begin{bmatrix}0&1&\frac{\sin b}{b}&0\\1&2&0&0\\1&a^2&0&0\\0&0&\frac{\sin b}{b}&0\end{bmatrix},\quad A_3=\begin{bmatrix}0&1&1&0\\1&2&0&0\\1&0&0&0\\0&0&1&0\end{bmatrix},$$

$$A_4=\begin{bmatrix}0&1&\frac{\sin b}{b}&0\\1&2&0&0\\1&0&0&0\\0&0&\frac{\sin b}{b}&0\end{bmatrix},\quad B_1=B_2=\begin{bmatrix}1+a^2\\0\\0\\0\end{bmatrix},\quad B_3=B_4=\begin{bmatrix}1\\0\\0\\0\end{bmatrix},$$

$$C_1=C_2=\begin{bmatrix}0&1&0&1+a^2\\0&1&1&0\end{bmatrix},\quad C_3=C_4=\begin{bmatrix}0&1&0&1\\0&1&1&0\end{bmatrix}$$

Supposing $a=0.6$ and $b=0.8$,the pole assignment of four subsystem as follow:

$$Pole1=[-1\quad -2\quad -0.96\quad -0.82],$$

$$Pole2=[-3\quad -5\quad -0.7291\quad -0.42]$$

$$Pole3=[-1\quad -5\quad -3\quad -2]$$

$$Pole4=[-1\quad -3\quad -0.9651\quad -5]$$

Then the state feedback matrix is:

$$F_1=[4.9853\quad 19.7671\quad -2.3501\quad -0.7059]$$

$$F_2=[8.1979\quad 31.7496\quad 4.2690\quad -2.2882]$$

$$F_3=[13\quad 106\quad -37\quad -15]$$

$$F_4=[11.9651\quad 78.8339\quad -21.3178\quad -8.0425]$$

Out layer: the QTS fuzzy model of nonlinear system is described as follow:

Rule 1:If $x_1(k)$ is M_{11}, $x_3(k)$ is M_{12},then the inner layer system 1 is:

$$x(k+1)=A_1x(k)+\sum_{r=1}^{3}\sum_{j=1}^{3}\mu_r\mu_jB_1F_{1j}x(k-r-j)+\sum_{r=1}^{3}\mu_r\mu_4B_1F_{14}x(k-r-1)$$

$$y(k)=C_1x(k)$$

Rule 2:If $x_1(k)$ is M_{11}, $x_3(k)$ is M_{22},then the inner layer system 2 is:

$$x(k+1)=A_2x(k)+\sum_{r=1}^{3}\sum_{j=1}^{3}\mu_r\mu_jB_2F_{2j}x(k-r-j)+\sum_{r=1}^{3}\mu_r\mu_4B_2F_{24}x(k-r-1)$$

$$y(k)=C_2x(k)$$

Rule 3:If $x_1(k)$ is M_{21}, $x_3(k)$ is M_{12},then the inner layer system 3 is:

$$x(k+1)=A_3x(k)+\sum_{r=1}^{3}\sum_{j=1}^{3}\mu_r\mu_jB_3F_{3j}x(k-r-j)+\sum_{r=1}^{3}\mu_r\mu_4B_3F_{34}x(k-r-1)$$

$$y(k)=C_3x(k)$$

Rule 4:If $x_1(k)$ is M_{21}, $x_3(k)$ is M_{22},then the inner layer system 4 is:

$$x(k+1)=A_4x(k)+\sum_{r=1}^{3}\sum_{j=1}^{3}\mu_r\mu_jB_4F_{4j}x(k-r-j)+\sum_{r=1}^{3}\mu_r\mu_4B_4F_{44}x(k-r-1)$$

$$y(k)=C_4x(k)$$

Supposing $\rho=\{0.3,0.5,0.1,0.1\}$

To simulate the system by using LMI (linear matrix inequality) of MATLAB, we can obtain the positive definite matrix:

$$Q=\begin{bmatrix}3&0&0&1\\0&3&0&0\\0&0&4&0\\1&0&0&5\end{bmatrix}$$ and

$$P=\begin{bmatrix}6.7929&0.2198&0.0880&0.0020\\0.2198&0.0280&0.5811&0.0689\\0.0880&0.5811&0.0013&0.0169\\0.0020&0.0689&0.0169&0.0058\end{bmatrix}$$

Which satisfy the matrix inequality in theorem 1.

According above conclusion, we can design the observer of nonlinear NCS, furthermore we can do some research in fault diagnosis and tolerance control of nonlinear NCS.

Conclusions

This study has proposed a new model of nonlinear NCS based on quasi T-S fuzzy model which has considered time-delay and data packet dropouts synthetically. A Stability condition of this model has given in this paper,and a serial designing and analysis method can be used based on this.

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